Modelling and Simulation of Photovoltaic-Variable Speed Diesel Generator Hybrid Power System for Off-Grid Rural Electrification

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***Abstract*-This paper presents the modelling and simulation of a Photovoltaic-Variable Speed Diesel Generator (PV-VSDG) Off-Grid hybrid power system for long term analytical performance studies. Two different types of diesel generators, namely the constant speed diesel generators (CSDG) and the VSDGs were considered for the simulations. The system components have been developed using MATLAB/*Simulink*. The simulation results from *Simulink* were validated through comparison to the results obtained from the Hybrid Optimisation Model for Electric Renewable (HOMER) simulation software. *Simulink* models were then used to evaluate the performance of all system configurations. Based on the analysis, it was found that systems using VSDGs perform better than those with conventional CSDGs. The developed models can be modified and used to study the systems' performances using different power management strategies.**

Keywords-Renewable energy; solar energy; remote power system; supervisory control; modeling

I. INTRODUCTION

To date, there are still many inhabitants living in isolated areas of developing countries who have no immediate access to the main electricity grid. Most of these isolated communities rely on diesel operated power systems to generate electricity. Diesel operated systems are widely used due to their availability and affordability to most consumers. It is not uncommon to find various small-scale privately owned diesel generators (DG) in isolated areas supplying a number of households with their daily energy needs. Fig. 1 shows one example of a small diesel generator supplying energy to the nearby houses on Mabul Island, East Malaysia.

Figure 1. A remote island community powered by diesel generator

Other power systems serving larger groups of consumers are normally operated by independent power producers within the community. In those systems, diesel generators have to be sized to meet the peak load demand, which lasts for only a short period of time in a day. Those generators are operating at constant speed and have to be operated above the minimum loading of approximately 40% of the power rating. Prolonged low load operations below the allowable minimum loading are contributing to premature ageing of the engine and inefficient burning of fuel [1]. In addition, the rigid operation range of the constant speed diesel generator (CSDG) also reduces the flexibility at the system level control. Studies have shown that diesel generators with variable speed operations perform better than the constant speed generators [1]. Instead of forcing the diesel generator to operate above the 40% of the power rating at a constant speed, variable speed diesel generator (VSDG) can be operated in between the sub-synchronous and super-synchronous speeds that gives efficient operation [2]. VSDG has the capability of using optimum speed for a particular output power that results higher efficiency of the generator operation. This allows the engine to operate at relatively low speed for low power demand and vice versa. Furthermore, VSDG has lower fuel consumption compared to the CSDG [2].

The needs to diversify away from fossil fuel generation due to concerns over emissions are encouraging the deployment of green energy which is environmentally benign. Although the technologies of non-conventional renewable energy such as wind and photovoltaic (PV) systems are maturing rapidly, they are still not as cost competitive as the conventional diesel power systems. Also, the main drawback of renewable energy is the unpredictable characteristics. Unlike the diesel generator with a steady power supply, renewable energy generator power production is subject to the fluctuations of the renewable sources. Therefore, both of these generators are usually combined to form a hybrid power system, which offers the best of both worlds.

Several research studies have provided an informative discussion of the various hybrid power systems.[3-10] However, the majority of the hybrid power systems reported in the literature comprise energy storage elements to store excessive renewable sources, meet the peak load demand, and maintain loading to the diesel generator. Inclusion of an energy storage element into hybrid power systems incurs additional investment costs. For instance, the initial cost of a

hybrid power system with a large battery bank may include the costs for the batteries housing, auxiliary components, delivery and installation. Another concern will be the life-span of the batteries. These elements have short lifetimes that require the elements to be replaced every five to ten years to ensure proper operation of a system [11]. In consequence, the used batteries have to be handled with caution or delivered for recycling. Unfortunately, the majority of developing countries lack recycling facilities, leading to the improper disposal of the batteries.

Among the various system configurations, the combination of renewable energy sources with a diesel generator supply without complex control is more viable for remote applications compared to a system with high penetration of renewable energy, which requires massive energy storage components and complicated system control. Due to these reasons, several researchers have proposed use of the hybrid power systems without the storage element. A simple but robust wind-diesel system without energy storage was introduced and the applicability of the system for remote areas has been discussed [12]. Other literature has studied the feasibility of an energy system without storage by retrofitting renewable energy generators into the existing diesel based systems [13]. An experimental study indicated the possibility of practical implementation of hybrid power systems without energy storage and the diesel generator was designed to meet the peak load [14]. The above cases were focused only on the standard diesel generator and there were no performance studies done for a system without energy storage employing VSDGs in the literature. Thus, this paper presents the original analytical performance studies of the photovoltaic-variable speed diesel generator (PV-VSDG) hybrid power system without the energy storage element. The PV-VSDG hybrid power system configuration without the energy storage element is shown in Fig. 2. The supervisory controller of the system gives highest priority to supply the primary load. Secondary loads such as the heating element, crops dryer or ice making device is optional to the system and the operation of this load is usually deferrable.

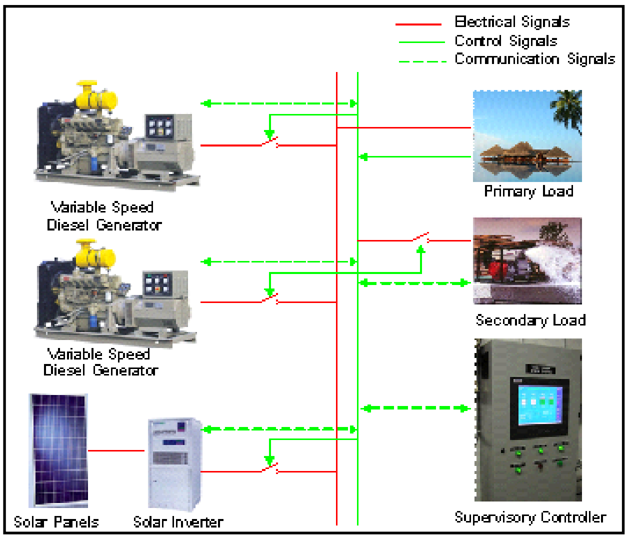
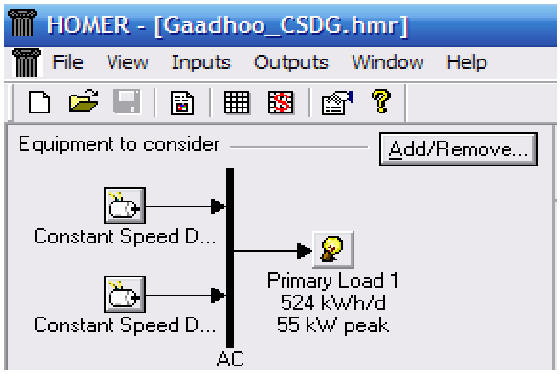
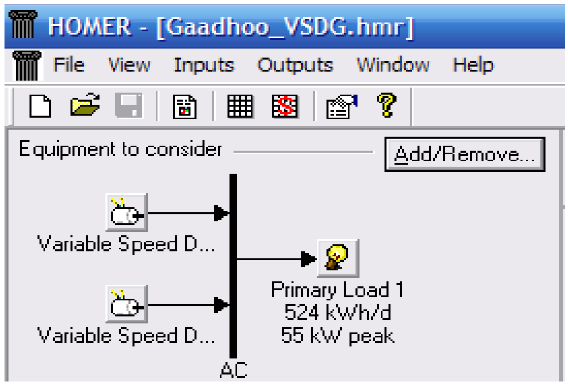


Figure 2. PV-VSDG hybrid power system without the energy storage element



(a)



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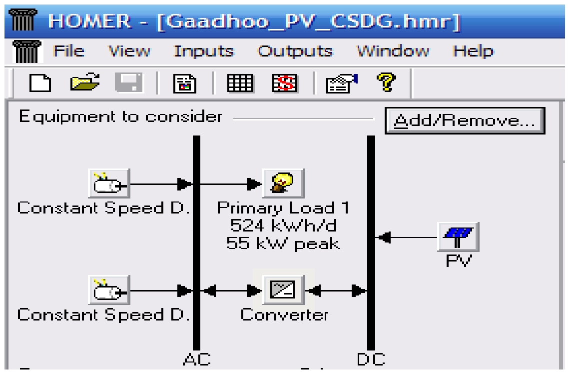

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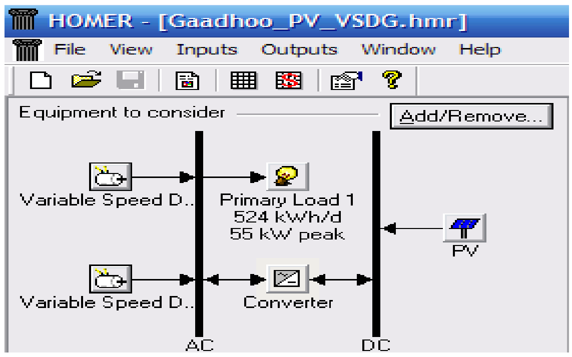


(d)

Figure 3. Off-grid power system configurations: (a) Configuration I, (b) Configuration II, (c) Configuration III, (d) Configuration IV

Simulations have been carried out to verify the system operation using the conditions as for Gaadhoo, in the Maldives (coordinates: 1° 49' 12" N; 73° 28' 11" E). The selected site has high solar radiation with monthly average insolations ranging from 5.38 to 6.77 kWh/m2/day and the annual average is 5.81kWh/m2/day.[15] Therefore, it is propitious to utilize this local renewable energy sources for green energy production in order to enhance the fuel savings of the off-grid hybrid power system.

In order to demonstrate the benefits of using VSDG in a hybrid power system, simulations are performed for four system configurations as shown in Fig. 3(a) – Fig. 3(d): CSDG-only system (Configuration I), VSDG-only system (Configuration II), PV-CSDG system (Configuration III) and PV-VSDG system (Configuration IV). Operational performance of the PV-VSDG hybrid power system will be compared to the other three alternatives'.

All system components were modeled using MATLAB/Simulink. The electrical simulation results of the micro-power optimisation software, HOMER, developed by the National Renewable Energy Laboratory (NREL), will be used for comparison and to validate the Simulink models. Simulink models were then used for analysing the operation and performance of the systems in terms of fuel consumption and carbon dioxide emissions. The reason for using Simulink for this purpose is because HOMER uses the linear fuel consumption model [16], which only fits the CSDG fuel consumption characteristic. This linear fuel consumption characteristic is not appropriate for the VSDG, where the fuel curve can be represented by a polynomial function [17]. Thus, a generic model of VSDG fuel characteristic was developed in Simulink and the model's parameters can be modified based on the manufacturer's datasheet for modelling of various sizes of VSDGs.

For the system operation in Simulink, one of the diesel generators will be selected as the grid-form generator which remains switched on all the time. This generator is therefore responsible for maintaining stable operation of the micro-grid. The additional generator will operate as the grid-feed generator, which is activated to meet the peak load demand. This grid-feed generator will be switched off when the grid-form generator alone is sufficient to meet the load demand.

The structure of the article is as follows: Section 2 discusses the system power management strategies; Section 3 elaborates on the procedures of data generation used for the simulation studies; Section 4 discusses modelling of the components; and Section 5 details the simulation results.

II. SYSTEM POWER MANAGEMENT STRATEGIES

The power management strategies discussed in this section is applied to the two categories of hypothetical systems mentioned previously, i.e.: DG-only systems and PV-DG systems. The "Load Following" strategy as described in [18] is adopted for the systems' power management. The core component for power management in an off-grid power system is the supervisory controller that operates to ensure a reliable power supply in spite of variations in the renewable power sources or the load demand while maintaining the diesel generators to operate within their power ratings. The system level power management involves dispatch and control strategies that determine the starting and stopping of the dispatch-able components such as the diesel generators and dump loads.

A. Power Management for DG-only Systems

For the systems consist of either CSDGs or VSDGs, the power management strategy is relatively simple. Basically, when the grid-form generator is sufficient to supply the primary load demand, the additional generator capacity will be switched off. The grid-feed generator will be activated to supplement the grid-form generator's supply only if the primary load demand exceeds the grid form generator's power rating. Fig. 4 shows the dispatch and control algorithm for this system configuration.

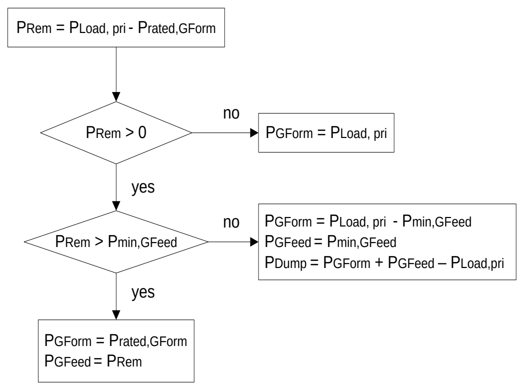


Figure 4. Dispatch and control algorithm for DG-only systems

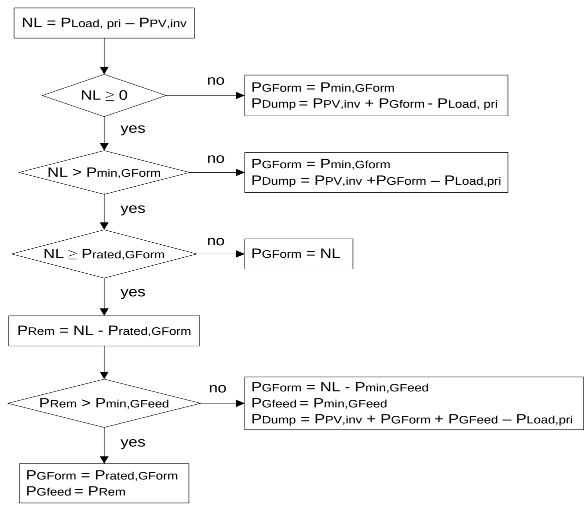


Figure 5. Dispatch and control algorithm for PV-DG systems

B. Power Management for PV-Diesel Generator Systems

For the system with renewable energy generator integrated, the overall power management strategy is depicted in Fig. 5. The renewable energy generator has the highest priority to supply the primary load demand. For the hybrid power systems considered in Section 1, the renewable energy supply is referred to the power generated from the PV generator through the inverter. The net load (NL), for the hybrid power

system after meeting the primary load requirement is calculated as the difference between the output from the PV power supply and the primary load demand. At any instance, when the renewable energy is sufficient to meet the load demand, the grid-form generator will operate to produce minimum output power while the surplus renewable energy is drained through the dump load. In contrast, whenever there is shortage of energy where the NL is greater than the minimum loading of the grid-form generator but within the grid-form generator's capacity, the grid-form generator will supply the NL accordingly. If the NL exceeds the grid-form generator's capacity, the grid-feed generator will be activated to supplement the energy supply.

III. DATA GENERATION

All system operations in this study are based on the weather condition and load demand of Gaadhoo, Maldives, with 84 houses and 416 inhabitants [19]. Simulation studies were carried out using real weather data obtained from the NASA meteorology website [15]. Also, the primary load demand of the selected site is estimated according to the power demand data given in [19] and the daily load profile of an outer island village in Maldives from [20]. The solar radiation, ambient temperature and the hourly average load demand profile of the selected site are shown in Fig. 6 to Fig. 8.

The time steps of the simulations are set to one hour. Synthetic hourly solar irradiance (kW/m2) and primary load demand data are generated using HOMER for 365 days. In order to obtain a set of synthesized solar irradiance data that is close to the measurements from the practical instruments, the relevant data given in Table I such as the properties of the PV panel and the PV array position are entered into HOMER for the synthetic data generation. For the selected site, the PV array has to be tilted at the optimal angle, which is equivalent to the local latitude of the site and the PV panels are oriented to the equator to maximize the PV outputs.

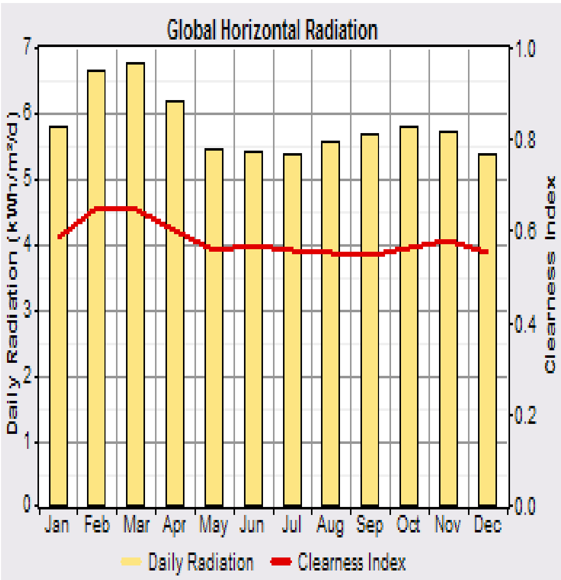


Figure 6. Solar radiation of Gaadhoo

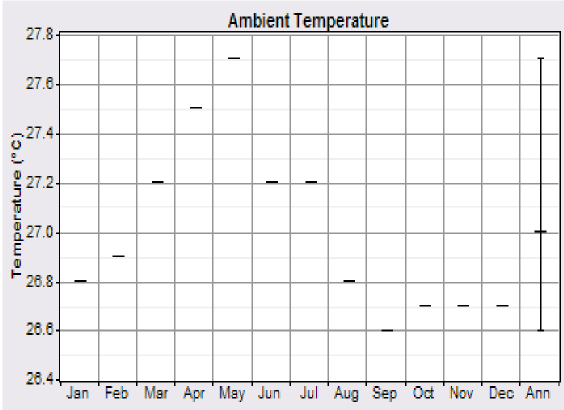


Figure 7. Average monthly ambient temeprature of Gaadhoo

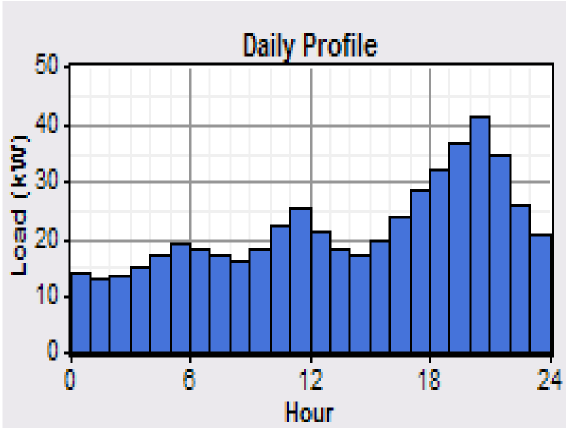


Figure 8. Daily load demand profile of Gaadhoo

TABLE I. SYSTEM COMPONENT PARAMETERS

PV model simulation parameters	
Slope / Tilt angle	1.82° (1° 49')
Azimuth	0°
Ground reflectance	20%
Panel Derating Factor	95%

On the other hand, a 10% of time-step to time-step randomness and a 5% of day-to-day random variability are input into HOMER to generate the load demand time series. All synthesized time series generated were used as inputs for the Simulink simulation as to be discussed in section 5. These time series were exported and saved in the MS Excel format. The synthetic data of the solar radiation and load demand were written to the MATLAB workspace and prior to importing into the Simulink.

IV. SYSTEM COMPONENT MODELS IN SIMULINK

The component models of the off-grid energy systems detailed in Section 1were designed to demonstrate the systems operational behaviour in steady-state with several components exchanging power with each other at a common Alternating Current (AC) Bus. In this section, simulation models of system components such as: PV, CSDG, VSDG and the supervisory controller are presented. All models described are used for investigating the systems' performances over one year duration of time and steady-state modes of operations are assumed. The accuracy of the Simulink models for each

individual component will be verified using the simulation results obtained from HOMER.

Photovoltaic

The PV model as shown in Fig. 9 [21] is adopted in this work for the Simulink simulation. This model comprises a current generator that represents the conversion of solar radiation to electric current, a single diode, a series resistance and a parallel resistance. The input variables to the model are the solar irradiance and the ambient temperature. Based on the PV cell model in Fig. 9, the mathematical descriptions of the PV equivalent electrical circuit are given in Eq. (1) to Eq. (3) where the short circuit current of the PV cell is proportional to the solar irradiance.[21] The PV module voltage and current can be obtained using Eq. (4) and Eq. (5) respectively. Assuming the maximum power point tracker (MPPT) is associated with the PV generator, the PV output power is the effect of solar irradiance striking on the panel. Given the meteorological data, the PV module power can be solved by computing the product of the PV module's voltage and current as in Eq. (6). In order to obtain the PV power at the inverter input, the power production from the PV array is given in Eq. (7).

$$I_{SC} = I + I_d + I_p \tag{1}$$

$$I_{cell} = (G \times I_{SC}) - I_0\left(e^{\frac{qV_d}{kT}} - 1\right) - \frac{V_d}{R_P} \tag{2}$$

$$V_{cell} = V_d - IR_S \tag{3}$$

$$I_{mod} = C_p \times I_{cell} \tag{4}$$

$$V_{mod} = C_s \times V_{cell} \tag{5}$$

$$P_{PV,mod} = V_{mod} \times I_{mod} \tag{6}$$

Where I_d is the diode current, I_p is the shunt resistance current, G is the solar irradiance, V_d is the diode voltage, q is the electron charge, k is the Boltzmann's constant, T is the diode junction temperature, R_s is the series resistance and R_p is the parallel resistance.

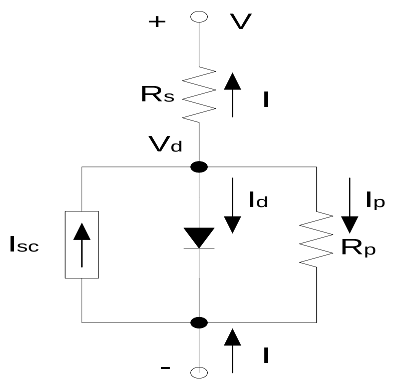


Figure 9. PV cell model

Taking the PV cell temperature and the module derating factor into account [21], the PV arrays will deliver:

$$P_{PV} = M \times P_{PV,mod} \times DF \times [1 + PD(T_{cell} - T_{cell\,.STC})] \tag{7}$$

Where M is the module number, DF is the module derating factor, PD is the module power drop coefficient, T_{cell} is the cell temperature and $T_{cell\,.STC}$ is the cell temperature under standard test conditions.

Information from the manufacturers' data sheets for a selected PV module that describes the module's properties are shown in Table II. [22] This data is entered into the simulation models to compute PV power with an acceptable accuracy.

TABLE II. PV MODULE SPECIFICATIONS

Parameters	
Solar Cell No.	72
Power rating	Peak power 210W @1kW/m^2, 25°C
Rated Voltage, V_{mpp}	40.0V
Rated Current, I_{mpp}	5.25A
Open Circuit Voltage, V_{oc}	47.7V
Short Circuit Current, I_{sc}	5.75A
NOCT	46°C +/-2°C

Fig. 10 shows the power generated from the PV array in Simulink depends on the synthesized data of solar irradiance and ambient temperature. The available PV power at the AC bus after the energy conversion through the inverter is given as:

$$P_{PV\_invm} = P_{PV} \times \eta_{inv} \tag{8}$$

where η_{inv} is the inverter efficiency.

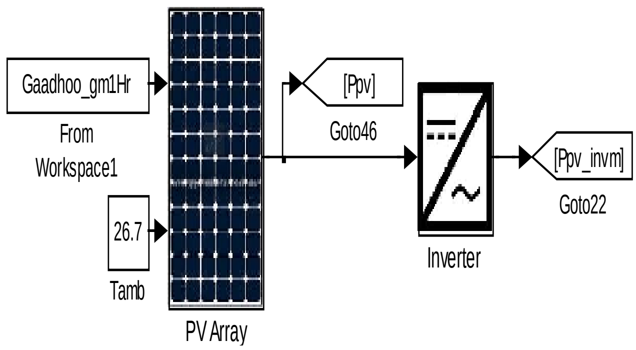


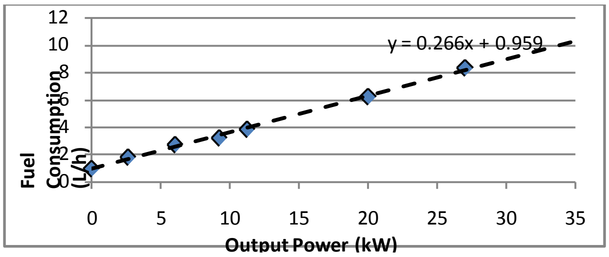
Figure 10. The PV generator model in *Simulink*

A. *Constant Speed and Variable Speed Diesel Generators*

As this study is focused on the long-term energy performance of the systems, the diesel generators in the systems are modelled for steady-state operations. Modelling of these components is based on the characteristics or measurements supplied by the manufacturer's datasheets. The model of a diesel generator is represented by the power versus fuel consumption characteristic. In HOMER simulation software, the fuel consumption characteristic of a generator is assumed as a linear equation. The linear characteristic may be adequately representing a CSDG; however, it is not appropriate for the VSDG model. The polynomial equation is

a better fit for the fuel consumption characteristic of a VSDG.[2]

The power versus fuel consumption curves of a CSDG and VSDG adopted in the simulations are shown in Fig. 11(a) and Fig. 11(b). [2] A no-load fuel consumption of 0.96L/hr is assumed for the CSDG and 0.67 L/hr for the VSDG, which indicates the VSDG consumes approximately 30% less fuel as compared to the CSDG. Also notable from the VSDG operation characteristic is its capability of producing higher power output above the synchronous speed. [2] In addition, the VSDG consumes less fuel than the CSDG in the normal operating range, i.e. the range between minimum loading and maximum power rating of a diesel generator. Since diesel generators operate below their maximum power rating most of the time, it is anticipated that long-term fuel consumption will be lower for a system employing VSDGs. The examples of *Simulink* models for CSDGs are shown in Fig. 12.



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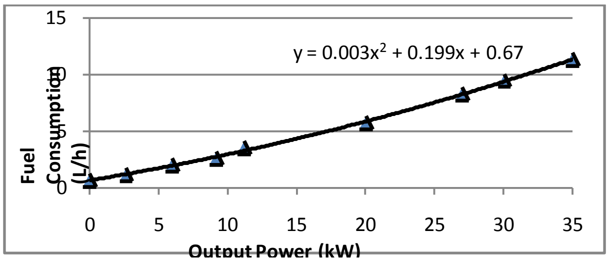


(b)

Figure 11. Fuel consumption versus power production of a: (a) CSDG, (b) VSDG

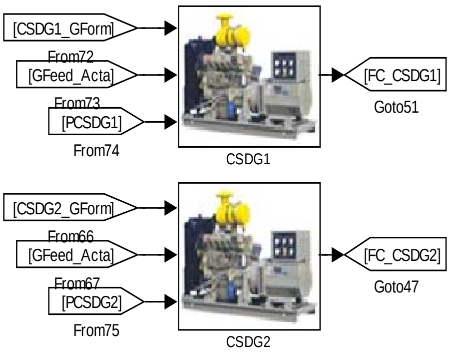


Figure 12. The diesel generator models in Simulink

C. Supervisory Controller

The supervisory controller is modelled based on the desired control strategies. Basically, the supervisory controller performs system level control to coordinate and supervise system operations while communicating with the components' local controllers and regulators. The model of the supervisory controller is shown in Fig. 13. Input data required by the supervisory controller are the operator defined inputs, electrical loads, solar irradiance and system components' ratings. Computations, planning and decisions will be carried out based on the operation conditions. In consequence, control signals from the supervisory controller will be sent to the local controllers of diesel generators and dump load in order to balance the system operation.

In Simulink, there is an additional function of the supervisory controller that assigns the diesel generators to operate as the grid-form or the grid-feed generator alternately according to their accumulated operating periods. Under this function, the machine with a longer operational period since last activation will be operated as the grid-feed generator when both of the generators are required at a certain period. This allows the grid-feed generator to be switched off, if the grid-form generator is capable to meet the net load in the coming period. This strategy is used to balance the operating hours of the generators in order to facilitate the maintenance schedules when dispatching technical service crews to remote areas.

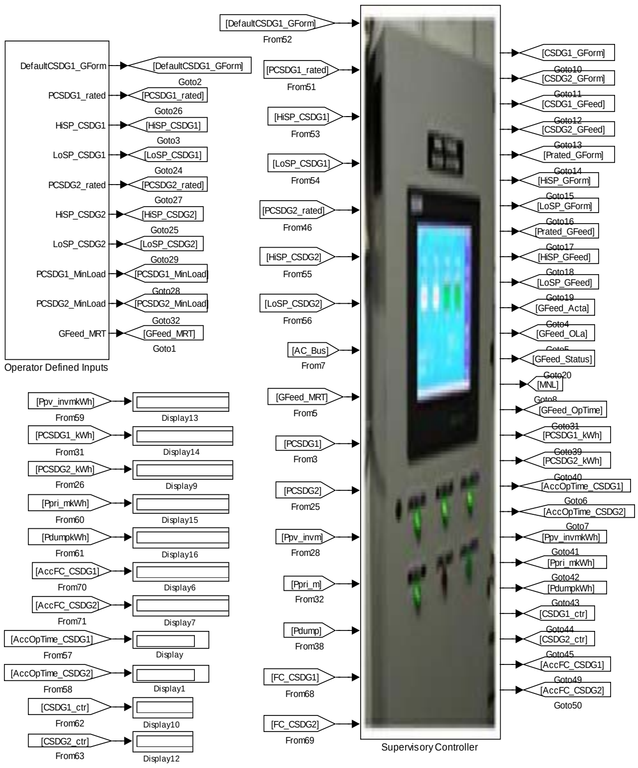


Figure 13. The supervisory controller model in *Simulink*

V. SIMULATION AND RESULTS

In order to validate the system operation for each configuration and the models developed in Section 4, the simulation results from Simulink are compared to the HOMER to ensure the components are modelled with acceptable level of accuracy. The time series of the PV power and load demand are compared to ensure the input data is comparable in both simulation software tools. Fig. 14 and Fig. 15 show the PV power generation and the primary load demand for seven days.

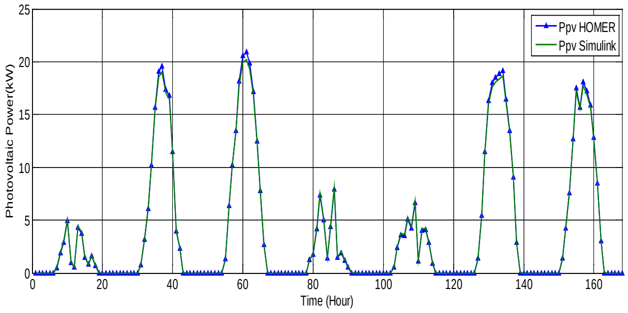


Figure 14. Simulation results of the PV power generation for seven days

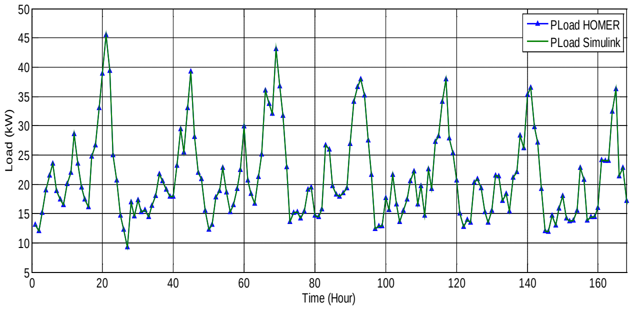


Figure 15. Simulation results of the primary load demand for seven days

Four simulation topologies as shown in Fig. 3(a) to Fig. 3(d), are studied and they are divided into the power systems that solely depend on the diesel generators and the hybrid power systems with a renewable energy generator integrated. The generators used in each configuration are identical and have the same power ratings. The annual hourly solar radiation and primary load demand time series are loaded into the MATLAB workspace prior to running the simulations. Same time series of the solar irradiance and the primary load demand were used for simulations to facilitate the comparisons of the simulation topologies.

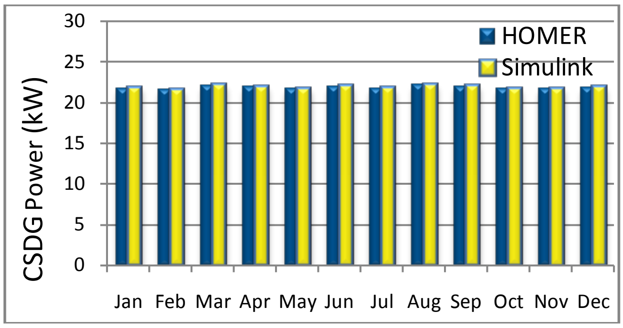
A. Diesel Generator-only System

The monthly power generation of Configuration I is shown in Fig. 16(a). Results from Simulink appear to be as good as the HOMER simulation results. The average monthly power production differences for this configuration are shown in Fig. 16(b) with the maximum magnitude of the differences not exceeding 0.003kW.

Fig. 17(a) illustrates the monthly power generated by the VSDGs in Configuration II. It is observed that the Simulink results show good agreement with the HOMER results. The majority of the average monthly power production differences between the simulation software tools as shown in Fig. 17(b) are negligible. Generally, both monthly power generations in Simulink are comparable to those in HOMER.

B. PV and Diesel Generator-only System

The PV generators in Configuration III and Configuration IV are identical and the output powers from the PV generators of these configurations are shown in Fig. 18(a). The PV model in Simulink produces monthly power productions that have minor differences from the HOMER's. The maximum average monthly power production differences are below 0.06kW as depicted in Fig. 18(b).



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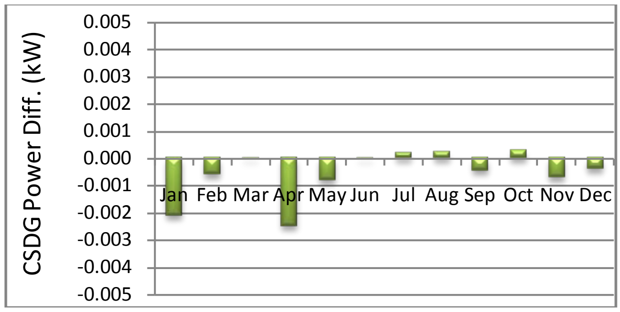
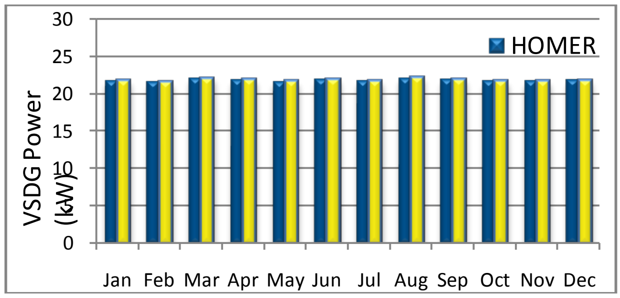


(b)

Figure 16. (a) Monthly CSDGs' power production from HOMER and *Simulink* for Configuration I, (b) Average monthly CSDG power production differences between simulation results from HOMER and *Simulink* for Configuration I



(a)

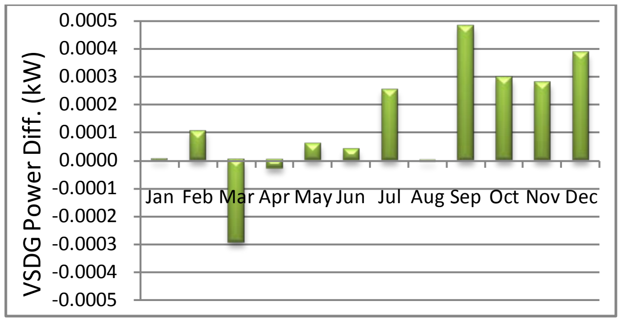


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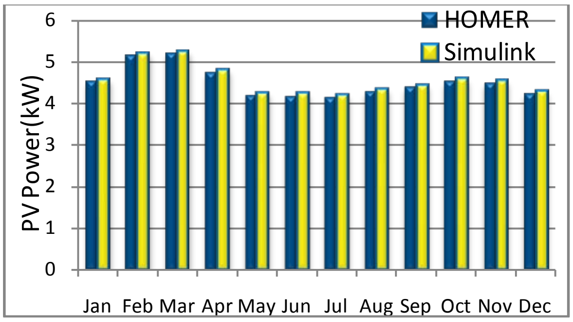
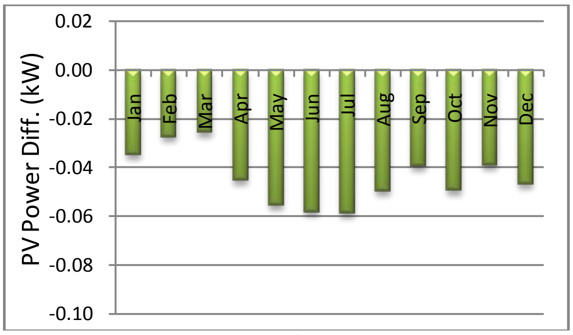
Figure 17. Monthly VSDGs' power production from HOMER and Simulink for Configuration II, (b) Average monthly VSDG power production differences between simulation results from HOMER and Simulink for Configuration II



(a)



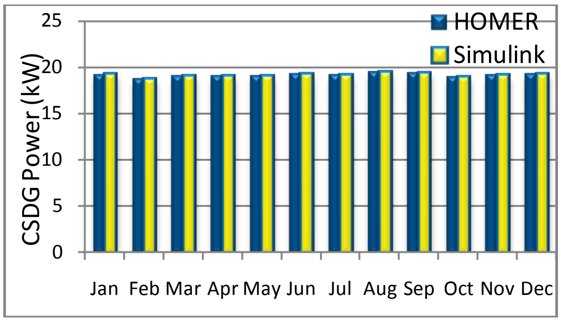
(b)

Figure 18. (a) Monthly PV generator power production from HOMER and *Simulink*, (b) Average monthly PV generator power production differences between simulation results from HOMER and *Simulink*

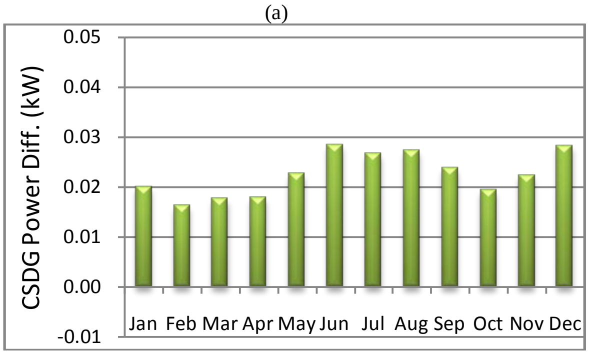
Operations of the CSDGs and VSDGs in the system Configuration III and Configuration IV were also simulated to examine the applicability and accuracy of these models when PV generators are considered in these systems. Fig. 19(a) gives a picture of the CSDGs monthly power production for Configuration III where the CSDGs power production in Simulink are equivalent to the HOMER results with low average monthly power production differences between 0.015kW to 0.03kW, as shown in Fig. 19(b). Fig. 20(a) and Fig. 20(b) show the VSDGs models in Simulink produces indistinguishable output power to the HOMER results with low overall average monthly power production differences below 0.17kW for Configuration IV.

Table III summarizes the annual power production and consumption for all simulation topologies under study. In general, annual operations of the systems obtained from Simulink are comparable to the HOMER simulation results. Simulation results of Configuration I and Configuration II from Simulink show good agreement to those given by HOMER. Under the adopted load following strategies, the CSDG-only system met the primary load demand with only a small amount of excess electricity dumped. Annual energy production for the VSDG-only system was slightly lower than the previous configuration with no excess energy dumped.

For the configurations incorporating PV generators, slight discrepancies of the simulation results were observed. This is due to the different PV model was adopted by HOMER while a detailed PV model was selected for the simulation topologies in Simulink. However, these discrepancies do not have significant effects on the annual energy supply. For Configuration III, 18% of the annual energy supply was contributed from the PV power generation. About 7% of the total annual energy production of this system was not utilized beneficially. For Configuration IV, the energy production from the VSDGs was lower than Configuration III and the unused energy was greatly reduced to less than 4%.

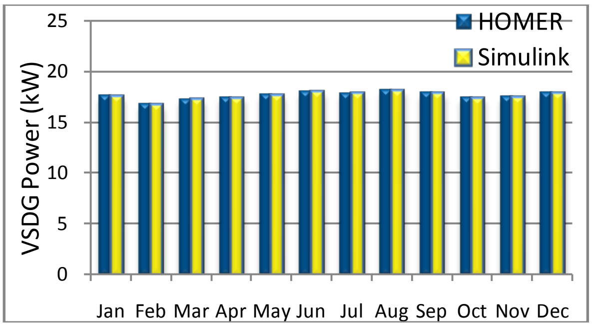


(a)

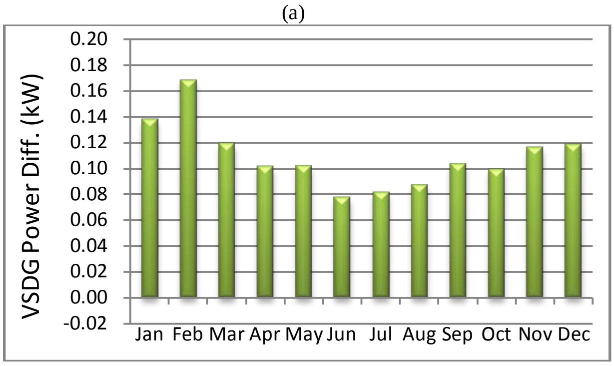


(b)

Figure 19. (a) Monthly CSDG power production from HOMER and *Simulink* for Configuration III, (b) Average monthly CSDG power production differences between simulation results from HOMER and *Simulink* for Configuration III



(a)



(b)

Figure 20. (a) Monthly VSDG power production from HOMER and *Simulink* for Configuration IV, (b) Average monthly VSDG power production differences between simulation results from HOMER and *Simulink* for Configuration IV

TABLE III. COMPARISON OF ANNUAL SIMULATION RESULTS FROM HOMER AND *SIMULINK*

Type	Parameter	HOMER		Simulink	
		kWh/yr	%	kWh/yr	%
I	Total CSDG production Primary load Excess electricity	191,428 191,257 171	100 100 0.09	191,433 191,259 173	100 100 0.09
II	Total VSDG production Primary load Excess electricity	191,259 191,257 0	100 100 0	191,259 191,259 1	100 100 0
III	PV production × η_{inv} Total CSDG production Primary load Excess electricity	37,458 167,246 191,257 14,145	18 82 100 6.91	37,826 167,047 191,259 13,613	18.5 81.5 100 6.65
IV	PV production × η_{inv} Total VSDG production Primary load Excess electricity	37,458 154,526 191,257 727	19.5 80.5 100 0.38	37,826 153,575 191,259 382.17	19.8 80.2 100 0.20

Simulation results of the systems' operations based on the load following strategies are shown in Fig. 21(a) to Fig. 21(d). Fig. 21(a) shows the operation of Configuration I for seven days where only a single generator is needed when the primary load demand is below the grid-form generator's capacity. If the primary load demand exceeds the grid-form generator capacity, the additional generator will be activated to supplement the power supply. For Configuration I, the small amount of excess energy will be drained through the dump load when the primary load demand is lower than the grid-form generator's minimum loading. Similar operational strategies are applied to Configuration II. Since the VSDGs have the advantage of a wider operation range and lower minimum generator loading, as mentioned in Section 3, there is no excess energy dumped in the operation of this system as shown in Fig. 21(b). The simulation results of hybrid power system Configuration III and Configuration IV are shown in Fig. 21(c) and Fig. 21(d). The primary energy supply of the hybrid power system is from the PV generators. When solar energy is available, and the net load is within the grid-form generator's capacity, only one diesel generator is required to operate on-line. Under certain circumstances, the surplus energy production is drained through the dump load due to the minimum loading constraints of the CSDGs and high solar energy production. The excess energy is reduced in the PV-VSDG system due to the lower allowable minimum loading of VSDGs, which leads to better system operation efficiency.

Fuel consumptions over forty-eight hours for all configurations are compared in Fig. 22. During day time operation between 6am and 6pm, fuel-use of Configuration I is higher than Configuration II. It is notable that systems with the integrated PV generator have lower fuel consumption, especially when there is excessive PV power. Among the four configurations, Configuration IV gives the most positive results with the lowest fuel consumption during day time operation. This indicates the potential of such a system to contribute significant fuel savings for long-term operation as compared to the conventional CSDG-only system.

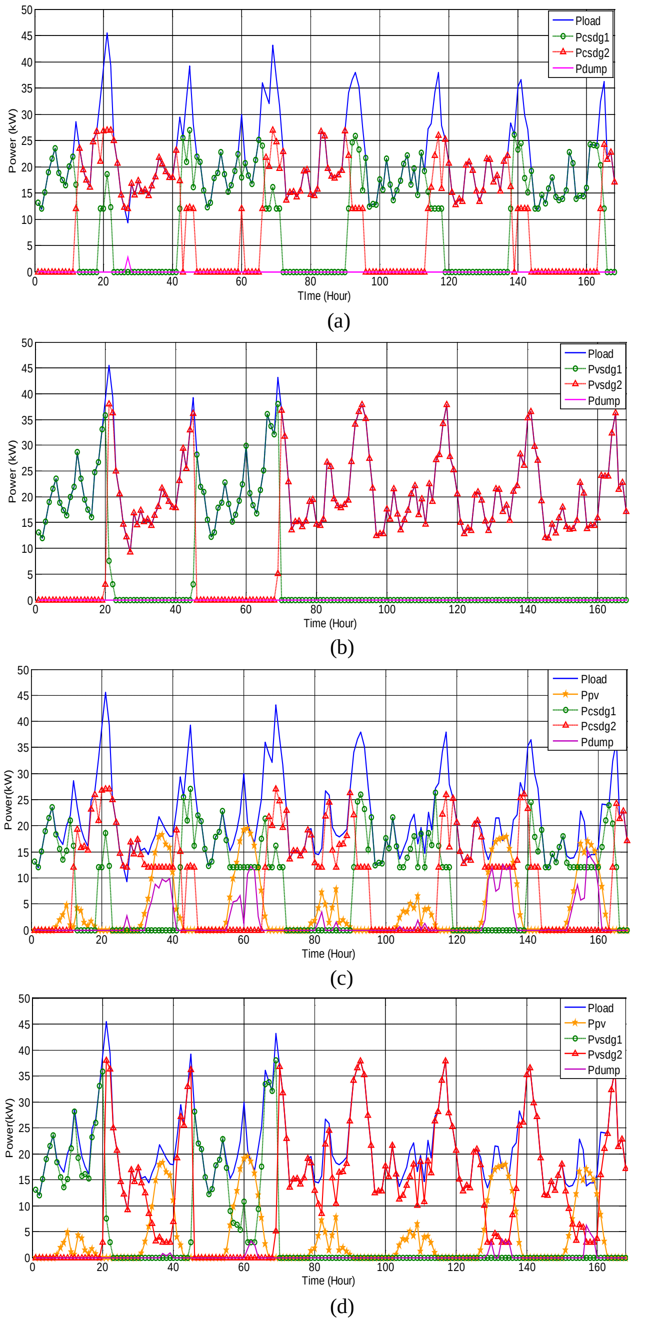


Figure 21. Seven days system operations for: (a) Configuration I, (b) Configuration II, (c) Configuration III, (d) Configuration IV

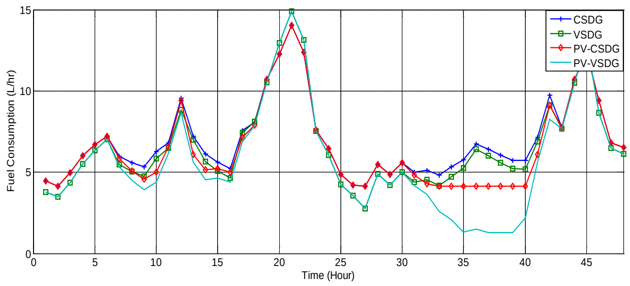


Figure 22. Comparisons of fuel consumptions over forty-eight hours for the four configurations

The fuel consumption and carbon dioxide emissions for all four configurations are summarized in Fig. 23. Configuration I resulted the highest fuel consumption, with more than 60,000 litres consumed, which leads to the worst annual carbon dioxide emissions. Configuration II consumed approximately 5.5% less fuel than Configuration I. System fuel consumption can be further improved when the PV generator is integrated. Configuration III consumed approximately 11% less fuel when compared to Configuration I. Configuration IV gives the most favourable results in terms of fuel consumption and carbon dioxide emission. This system consumed the least fuel among all the configurations and the carbon dioxide emissions are greatly reduced to nearly 23% than that of Configuration I.

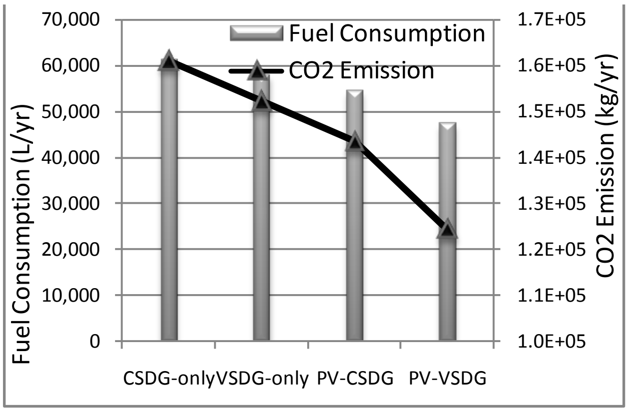


Figure 23. Fuel consumption and carbon dioxide emissions of the four configurations

VI. CONCLUSIONS

The system operations of four alternatives of off-grid power systems without energy storage element for the village in Gaadhoo, Maldives are discussed. Simulink was used to model these systems to study the performance of the systems using different types of diesel generators with and without PV generator. The system component models developed in Simulink have been validated by comparing the results of annual operation with the results obtained from HOMER and the comparisons show good agreement. The results obtained from Simulink have demonstrated the potential of a system employing VSDGs in terms of fuel savings and lower environmental impact. The VSDG-only or the PV-VSDG hybrid power system is found to outperform the CSDG-only and PV-CSDG hybrid power system respectively. Among all the configurations, PV-VSDG hybrid power system has demonstrated the capability to meet the primary load demand with the lowest fuel consumed and least excess energy produced. It is worth noting that, the Simulink models developed in this work can be extended to study the performance of any other off-grid hybrid power system with various renewable energy generators, provided the system operating characteristics and the site conditions are known. Furthermore, these models can be modified and used to study the systems' performances using different power management or system level control strategies.

ACKNOWLEDGMENT

The first author would like to thank the Ministry of Higher Education, Malaysia and University Malaysia Sabah for sponsoring the scholarship. Special thanks to Regen Power Pty. Ltd., Western Australia for providing technical information and advice. Thanks also to Josephine Smith from WordSmith WA for copyediting the article.

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